W, *Z*, and jets at the Tevatron Collider

Mel Shochet

University of Chicago

The goals of discovering new phenomena and making precision measurements to test the current paradigm were in play as the Tevatron Collider and its detectors were being developed. In the CDF TDR (1981):

- ***W/Z***
  - **Weinberg angle $\Rightarrow$ *W* & *Z* masses (83, 93 GeV)**
  - **Cross section at Tevatron an order of magnitude higher than at $S\bar{p}pS$**
    - **Trumped by a much earlier turn-on!**
  - ***WW* production with decay to 4 jets "should be distinctive"**
    - **First evidence came 16 years later, in the leptonic channels, because the QCD background was so large.**
- **Jets**
  - **Dijet cross sections were calculated to leading order in QCD**
  - **>2-jet events noted as important for studying the strong interaction**
  - **Particle flow within jets and between jets couldn't be calculated yet because of non-perturbative emission of low-energy gluons.**

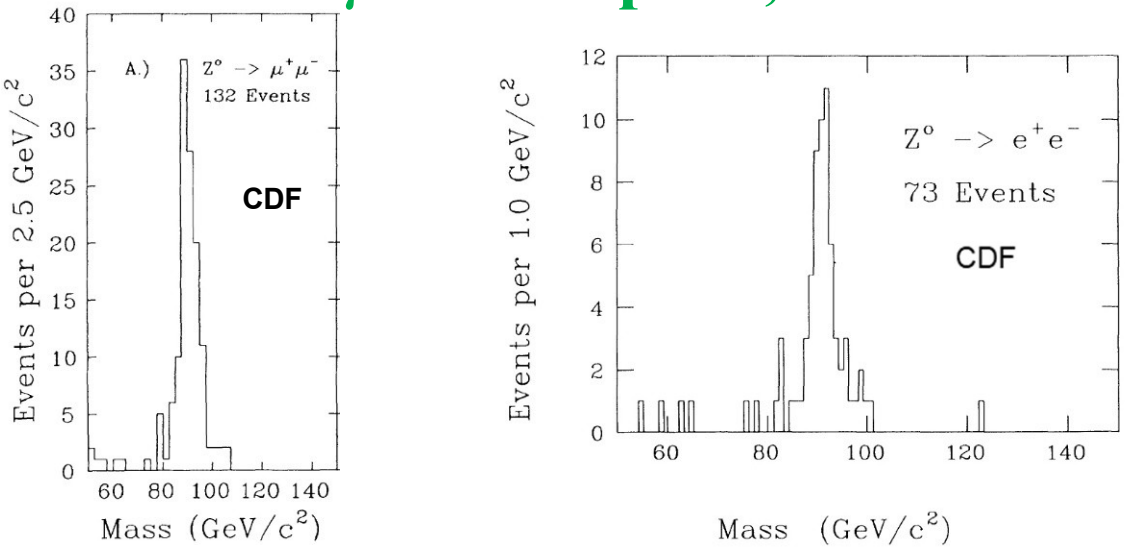
Intermediate Vector Bosons

- **W and Z already discovered when CDF and D0 began.**
- **Higher production cross section allowed for more precise measurements of W/Z properties $\Longrightarrow$ more stringent tests of the Standard Model.**

Z Mass (CDF, August 1989)

- **Rush to publication prior to SLAC's imminent result**
  - **Natural competitive nature of scientists to get an important result first**
  - **Counter the long-held belief that**
    - **e^+e^- colliders are precision machines, while hadron colliders are not due to messy environment.**
    - **Hadron colliders are discovery machines; lepton colliders are needed to map out the properties in detail.**
  - **Here was a chance to show that a hadron collider could make precision measurements.**
  - **If the hadron collider result was published first, it would be noticed. If it came second, it would be a footnote at best.**

- **The best measurement at the time had 2-3 GeV uncertainty.**
- **125 events in CDF $\mu^+\mu^-$ mass peak, 60-65 in e^+e^- peak**



$$M_Z = 90.9 \pm 0.3\ (\text{stat+syst}) \pm 0.2\ (\text{scale})\ \text{GeV} \quad (< 0.5\%)$$

- **Smallest uncertainty in muon channel**
  - **Momentum scale from large J/ψ and Υ samples (0.1% precision)**
- **Published without refereeing upon request by lab director (PRL policy)**
- **In PRL article immediately following the CDF paper, Mark II at SLAC reported $M_Z = 91.11 \pm 0.23$ GeV.**

- **I received a note from a friend on one of the LEP experiments:**

  "The CDF result on the *Z* mass is being received with shock and dismay by all competitors. Congratulations on a beautiful piece of work!! The timing too is impeccable."

- **In a memo from Burt Richter to John Peoples:**

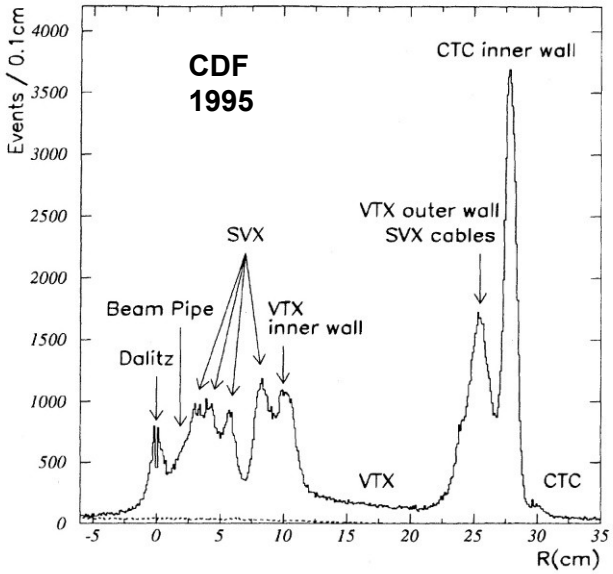
  "I really can't complain about CDF's success in beating the Mark II Collaboration to Phys Rev Letters with a paper on the Z mass … We out here have only ourselves to blame for perhaps taking a too relaxed attitude"

  "The press release is, however, another matter. You and your colleagues at Fermilab knew very well that your 'most precise measurement' had a life time as the 'most precise' of exactly two days. The press release clearly was a calculated attempt to exalt your efforts and to increase the positive publicity for Fermilab"

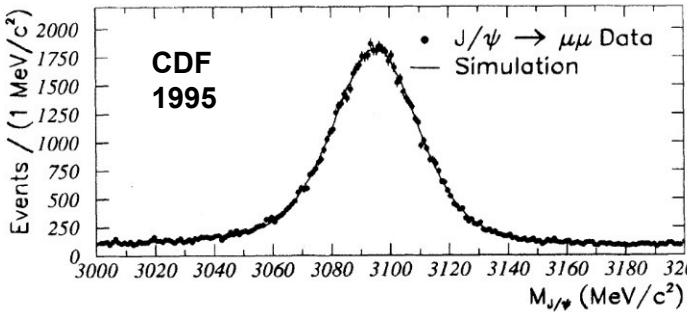
- **This, of course, is what lab directors do, try to increase the reputation of their labs in the eyes of the public and the funding agencies by publicizing new, important results.**

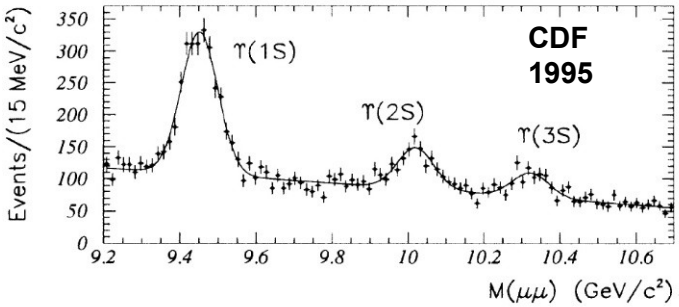
W Mass

- **The most important and most challenging precision measurement at the Tevatron Collider**
  - **Importance**
    - **An essential ingredient in a precision test of the SM**
    - **No big advantage for lepton colliders as there is for the *Z***
  - **Challenge**
    - **Because of large QCD background and difficulty of jet energy reconstruction, the focus had to be on leptonic decays**
    - **The *ν* transverse momentum inferred from overall momentum balance $\Rightarrow$ premium on accurate momentum measurement of all particles produced in the interaction. (The component of the *ν* momentum along the beam direction isn't measurable.)**
    - **With *W* mass precision approaching 1 part in 10^4, detector calibration is central to the measurement. Calibration involved many more scientists than those working on the *W* mass.**

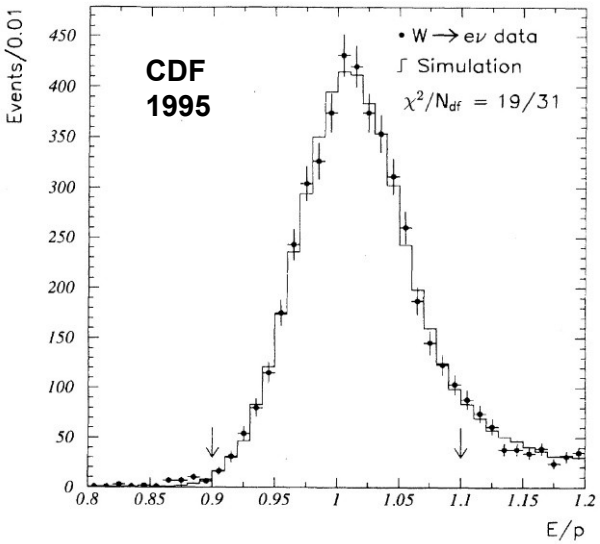


Detector material from photon conversions

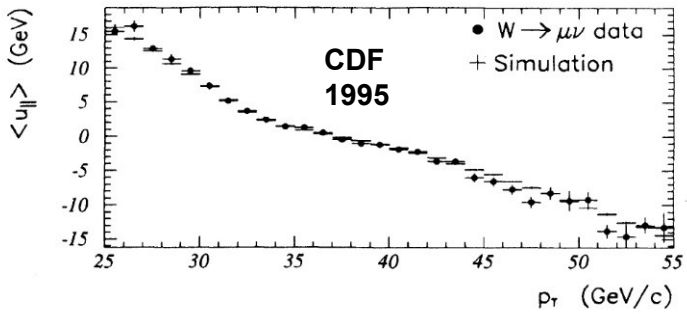




Momentum scale used large samples of J/ψ & $\Upsilon \rightarrow \mu\mu$



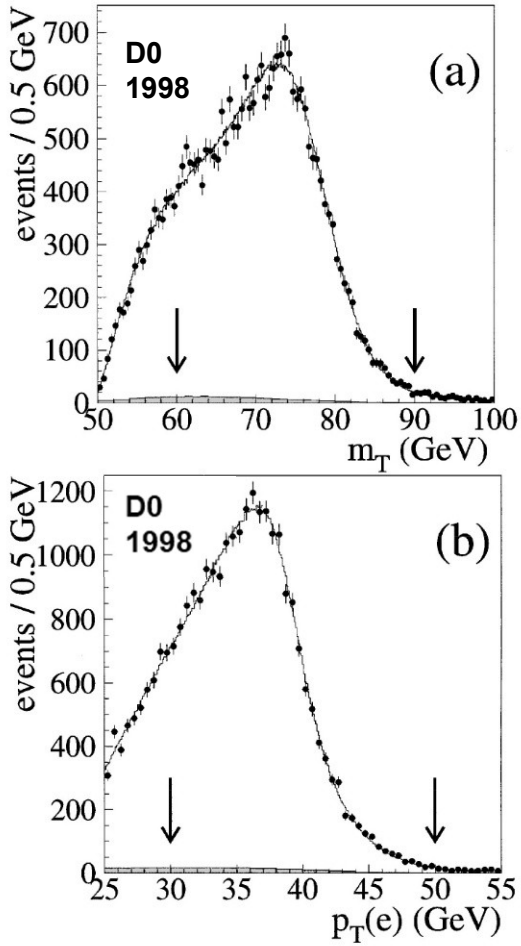
Calorimeter calibration used E/P



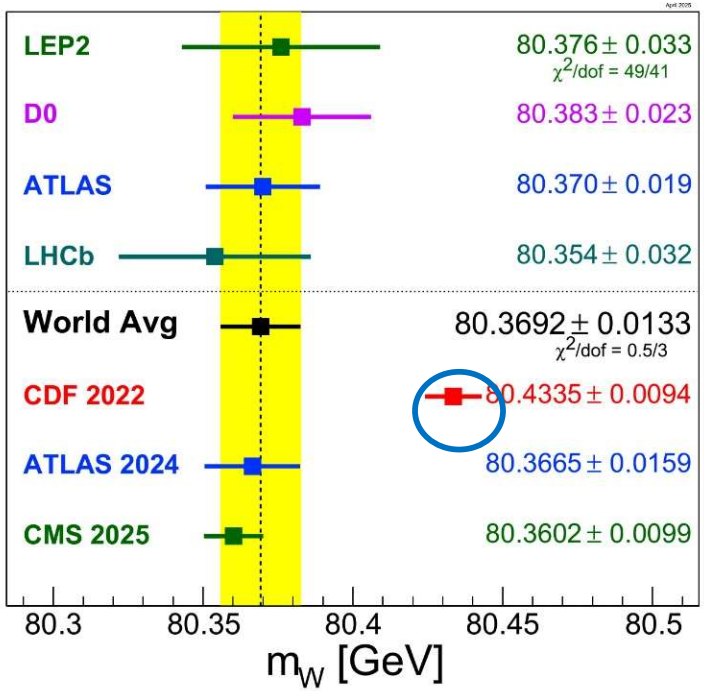
Simulation of the recoil to the W used Z events

- **The *W* mass is determined by a fit to the transverse mass distribution, ignoring the longitudinal component of the momenta since the neutrino's is unmeasured.**
- **Detailed systematic studies ⇒ papers took a long time to complete.**

CDF:	**1990**	**1000 events**	**0.49%**
	1995	**10000 events**	**0.22%**
	2001	**45000 events**	**0.10%**
D0:	**1996**	**6000 events**	**0.33%**
	1998	**28000 events**	**0.14%**
	2000	**+ 11k forward**	**0.11%**



- **Mass analyses continued long after Tevatron Collider stopped**
  - **Further reduction of systematics required larger data samples**
  - **D0: 2012 1.7M events 0.029% (80.375 ± 0.023 GeV)**
  - **CDF: 2014 1.1M events 0.024% (80.387 ± 0.019 GeV)**
- **These results satisfied the Standard Model test.**
- **But this is not quite the end of the story. When dealing with a 1 part in 10^4 measurement, subtle systematic effects can have a significant impact.**
- **CDF: 2022 4M events 80.4335 ± 0.0094 GeV**
- **This is in significant tension with previous measurements and with later ATLAS and CMS results. Work to understand this result is ongoing.**



Jets

- **Jets from scattered quarks and gluons were discovered and initially studied at e^+e^- colliders and the *$S\bar{p}pS$*.**
- **Role of the Tevatron Collider**
  - **Study QCD in more detail and at higher orders in perturbation theory**
  - **Help improve modeling of non-perturbative effects**
  - **Use jets as a tool for searching for new phenomena**

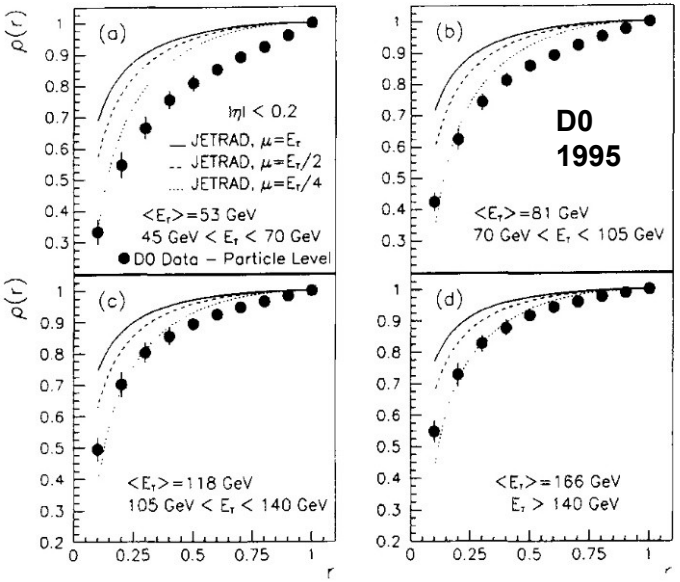
Calibration

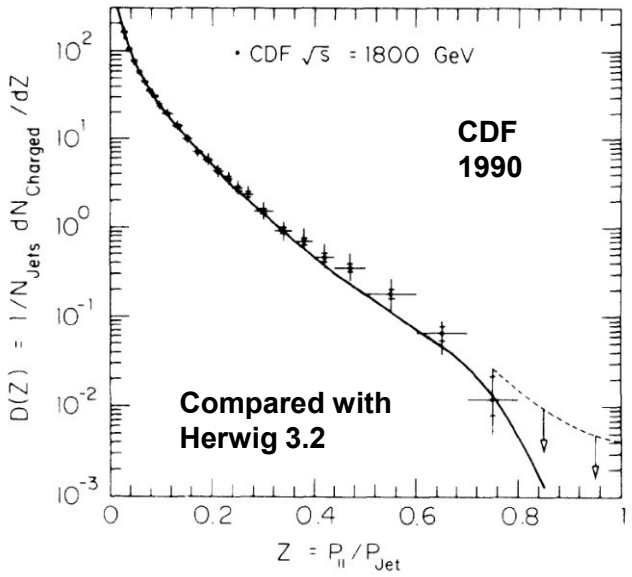
- **Here needed to get moderate precision on the parent quark or gluon energy.**
- **Early in an experiment's existence, the team is developing techniques and trying to understand the detector. This sometimes involves comparing performance with that of previous experiments, even though the detectors are not identical. Ex. From initial 1987 studies of the CDF detector.**

  "UA2 sees at 40 GeV a single pion resolution of approximately 12%. From jet E_T balancing studies, they estimate for the same energy jet their resolution is approximately 14%. In CDF, at 50 GeV, a single pion has roughly a 10% resolution – whereas for a jet at the same energy … preliminary indications … the resolution … is more like 18% … that disparity between UA2 experience and what is seen for CDF is bothersome and cause for concern"

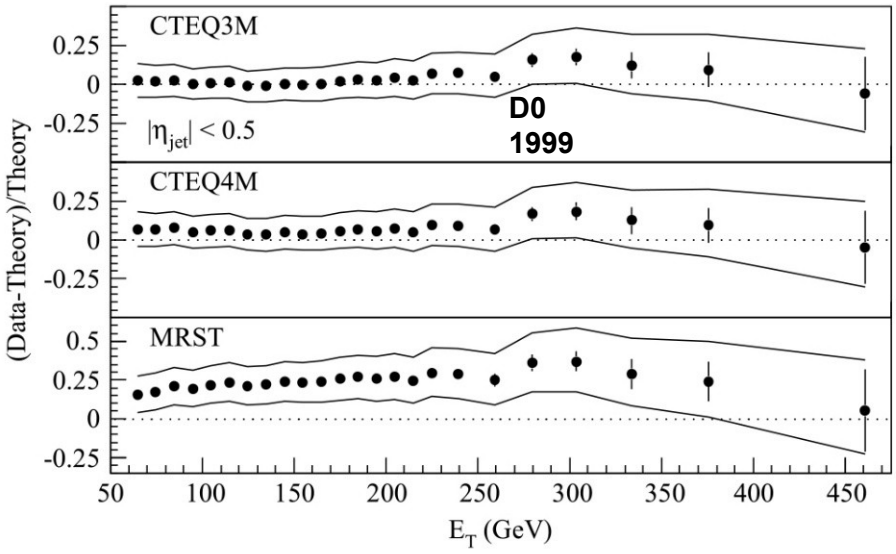
- **With more studies and better simulation, such concerns were resolved.**

- **Continuing interplay between experiment and theory**
  - **Fixed-order jet production**
  - **Modeling of the jet itself**
    - **Particle and energy flow inform non-perturbative modeling improvements**
    - **Need to remove energy in a jet coming from additional collisions and the underlying event.**
      - **Initially, a simple average subtraction scheme**
      - **Later, especially at the LHC, schemes developed to separate clusters of energy within a jet that come from the fragmentation of the quark from the rest of the jet.**

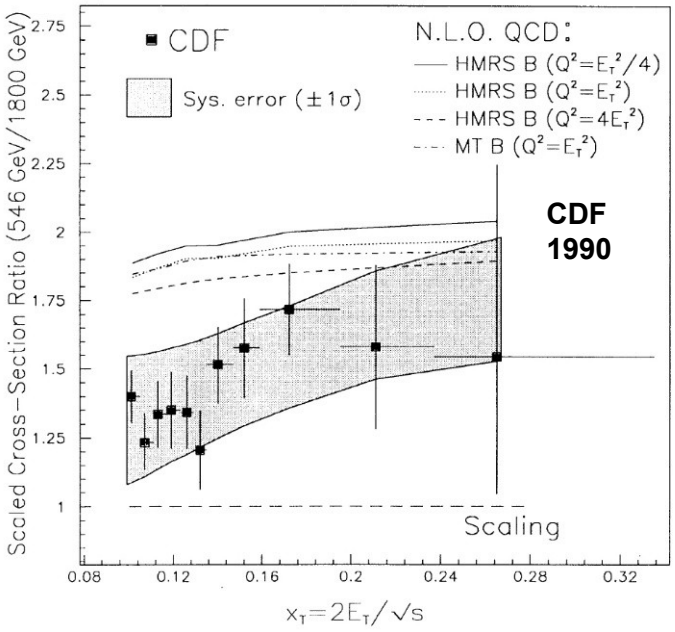




- **Inclusive jet production**
  - **Need to include hadron collider data into parton distribution functions.**
  - **Then all pdfs are fine.**



- **Ratio of jet cross sections for 546 and 1800 GeV**
  - **Short 546 GeV run to compare with UA2 (fine)**
  - **QCD test with low systematics**
  - **Shape didn't look like QCD, but uncertainties still significant ⇒ lots of internal debate**



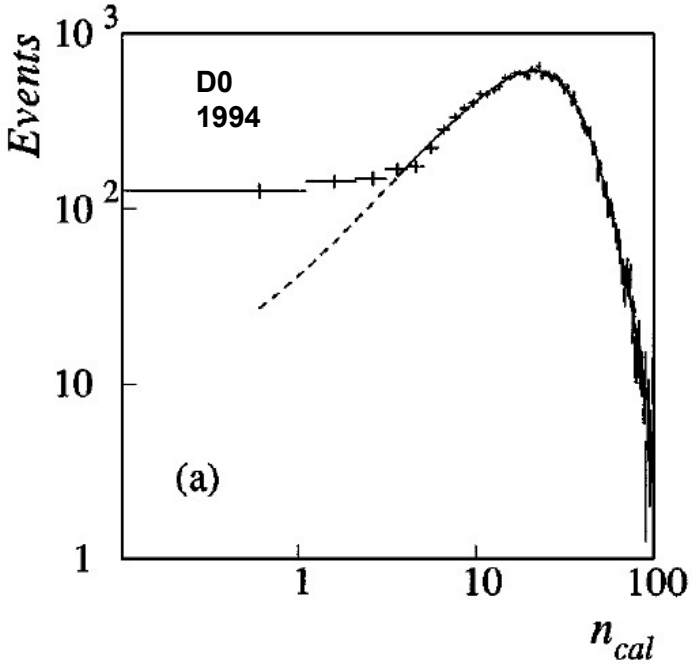
- **Bjorken's statement to me:**

CDF and D0 will never publish a result that disagrees with the SM because the internal debate would never end.

Sociology of large collaborations

- **Sometimes there are topics that a small fraction of the collaboration is passionate about, while the rest of the collaboration has passing interest.**
  - **Example in CDF: diffractive physics and "what is the Pomeron"**
    - **The bulk of the total cross section, not easily described by QCD**
    - **One connection to jet production – rapidity gaps where the region between 2 jets is almost devoid of particles because there is no color difference between the fermions producing the jets.**

- **D0 looked for rapidity gaps by counting the number of calorimeter cells above a low energy threshold.**
  - **$1.07 \pm 0.10^{+0.25}_{-0.13}$% consistent with 2-gluon color-singlet exchange**



- **Tension can exist between scientists who see something they feel may be a new phenomenon and the bulk of the collaboration that typically is conservative about making such claims (BJ's comment again). Ex: CDF Superjets**
  - **Heavy-flavor jets produced in events with a *W* boson**
    - **Identify a *b*-jet from either a secondary vertex or a low P_T electron or muon in the jet.**
    - **They saw a larger than expected number of jets with both a secondary vertex and a soft lepton (superjet).**
      - **Observed 13 *W*+2or3-jet events with a superjet**
      - **Expected 4.4±0.6**
    - **Internal review committees and many collaboration meetings.**
    - **Many were not convinced it was new physics (trials factor, *a priori*, …)**
    - **Decided to report the observation in a paper under the collaboration byline without a statement about the likely origin of the events.**
    - **A separate paper in which the production of a light scalar quark was considered was not signed by the collaboration but by a dozen physicists who chose to sign.**

Concluding Remarks

- **The hope for the Tevatron collider, CDF, and D0 was for the discovery of new phenomena. (top quark) (*W's* and jets)**
- **Way beyond expectation was the precision that could be obtained at a hadron collider (*W* mass and the *Z* mass earlier)**
- **For hadron jets, there were important tests of QCD with the large samples of 2, 3, and 4-jet events. Equally important was the collaborative efforts among experimentalists and theorists to better model the Bremsstrahlung and fragmentation processes that determine the constitution of jets.**
- **The legacy was the ability to use *W*'s, *Z*'s, and jets as tools in the search for new phenomena that might help resolve open questions in the Standard Model. These would be used exquisitely by the LHC experimenters as they opened the very large new phase space that 13-14 TeV center-of-mass energy provided.**